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ACCELERATED CORROSION TESTING OF GRAPHITE/EPOXY COMPOSITES AND ALUMINUM ALLOY MECHANICALLY-FASTENED JOINTS

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The purpose of this program was to evaluate the effectiveness of a currently used finishing system to protect graphite/epoxy composites mechanically fastened to aluminum substructures with either titanium or A-286 CRES fasteners. Lap joint samples of laminated graphite/epoxy $(\pm 45/0_2/90)_4/\pm 45/0)_s$ and aluminum alloy plates (2124-T851) were fabricated using either titanium (NAS1154V4) or A-286 CRES (MS 21140) fasteners. The unprotected baseline samples were fabricated by installing the fasteners in the uncoated graphite/epoxy aluminum alloy plates. The protected samples consisted of the finishing system currently used on the F-16 aircraft. The samples were exposed to humidity and salt fog for twelve weeks, tested in fatigue and exposed to the corrosive environment for twelve more weeks. The extent of corrosion was evaluated by both visual and microscopic examination. (Continued)

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The unprotected samples experienced severe galvanic corrosion of the aluminum plate. The formation of the corrosion products between the composite and the aluminum alloy plate resulted in gross deformation of both the aluminum and composite. The protected samples with the finishing system similar to that used on the F-16 aircraft represented an improvement in resistance to corrosion compared to the unprotected samples. The accelerated testing of the protected samples indicated the following problems: (1) If the area where the composite butts together in the lap joint was not properly sealed galvanic corrosion could occur in the aluminum. (2) If the composite was not painted on the edge, severe pitting of the primed aluminum alloy plate would occur on the edge of the aluminum plate. (3) The titanium fasteners performed better than the A-286 CRES fasteners. The A-286 CRES fasteners corroded around the center pin of the fastener and corrosion of the aluminum occured where the crimped portion of the fastener contacted the aluminum plate. There were no discernible differences in the corrosion behavior of the samples exposed to corrosion cycles only and those samples exposed to both corrosion and fatigue testing.

PREFACE

This report describes the in-house effort conducted by the Preliminary Design Group (FIBCA), Structures and Dynamics Division (FIB), Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 2401, "Structures and Dynamics," Task 240103, "Structural Concepts," Work Unit 24010350, "Assessment of Corrosion Control Protective Coatings."

This program was a cooperative research effort between AFWAL/FDL, AFWAL/ML, and the Graduate Materials Engineering Program at the University of Dayton. Specimen fabrication was acomplished by AFWAL/FIBCC under the supervision of Mr R.T. Achard. Fatigue testing was conducted by AFWAL/FIBEC under the supervision of Mr H.D. Stalnaker. The corrosion testing was conducted by Dr James A. Snide under Contract F33615-79-C-3030 at the University of Dayton. The evaluation of the samples after corrosion and fatigue testing was conducted by Mr S.D. Thompson of AFWAL/FIBCA and Dr James A. Snide. Project Engineer for this effort is Mr Billy L. White

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INTRODUCTION

The demand for increased aircraft performance, as well as improved fuel efficiency, dictate increased usage of advanced composite materials. Of the advanced composite materials, graphite/epoxy promises the highest probability of achieving these goals. Graphite/epoxy has both high strength-to-weight as well as stiffness-to-weight ratios, resulting in a material which lends itself well to high performance aerospace applications. Due to these outstanding properties, plus demonstrated performance in secondary structures, graphite/epoxy composites may be used in primary aircraft structures. It is of the utmost importance that this material have a high degree of durability. Corrosion can seriously degrade the durability of structural components; therefore, the corrosion resistance of graphite/epoxy-aluminum structures under cyclic loading is an important question.

Studies have been conducted to determine corrosion behavior of graphite/epoxy and graphite/epoxy coupled to metals (1, 2, 3). These studies have concluded graphite/epoxy alone, or when attached to itself, is quite corrosion resistant. However, when joined to many structural metals, these materials act like cathodes and promote galvanic corrosion of the less noble metal (Anode). When graphite/epoxy composites are coupled with aluminum, the potential difference is more than one volt This is sufficient driving force to cause considerable corrosion of the

aluminum substructure resulting in decreased structural durability.

The critical area of an aircraft structural component is in and around fastener holes. It is in this area that graphite-epoxy can come in direct contact with dissimilar metals (fasteners and metal substructures). In-service experience and laboratory experiments have shown that the finished systems in these areas must be exceptionally good to prevent corrosion. A technique known as material isolation is currently being employed by the aerospace industry to protect these areas. In this technique, each material is coated with an organic material in order to isolate them from each other. The isolation system, used on the vertical stabilizer of the F-16, is shown in Figure 1. Similarly, sealant is added during the installation of the composite skin to the front spar of the vertical stabilizer as shown in Figure 2. A concern is that the cyclic, structural loads imposed upon the structural components may wear or crack the protective coatings and sealants providing sites at which local galvanic corrosion may occur.

The purpose of this program was to evaluate the effectiveness of the present corrosion protective scheme of mechanically-fastened composite structures after being exposed to cyclic structural loads and corrosive environments. The program consisted of the following parts: (1) accelerated humidity and salt fog testing before and after cyclic loading; (2) environmental exposure at the outdoor test site at Cape Canaveral, Florida. This report covers the results obtained from the accelerated corrosion testing.

SECTION II

EXPERIMENTAL PROCEDURE

1. TEST SPECIMENS

Ninety test specimens were fabricated of graphite/epoxy, aluminum alloy plate using either titanium alloy or A-286 CRES fasteners. Figure 3 is a sketch showing the cross-section of each type test specimen and the location of sealants and protective coatings. This lap-joint configuration was selected to permit movement within the joint when undergoing fatigue loading. Working of the sealants within the joint was of utmost importance if a valid assessment was to be made of the protective system's capability to prevent corrosion during operational use.

The graphite/epoxy portion of the specimen simulated typical aircraft composite skin structures. It was fabricated using Hercules AS-1/3501 material with a laminate orientation of $[(\pm 45/0_2/90)_4/ \pm 45/0]_s$. A glass scrim cloth was the last layer on the lower surface of the composite. Two composite plates (1.95 x 6.0 in) were mechanically attached to one plate of 2124-T851 aluminum (1.95 x 4.0 in). The composite plates were cut from a larger panel (25 x 12 in) using a diamond cut-off wheel. The large composite panels were layed-up by hand and cured in an autoclave (350° F, 2 hrs, 100 PSI). The countersunk holes in the composite were drilled with carbide drills. The composite plates were then attached to the aluminum alloy plate using either titanium (NAS 1154V4) or A-286 CRES (MS 21140) fasteners. The aluminum plate used on each specimen was cut from a larger piece of sheet stock and machined to size.

Table 1 lists the number and type of test specimens used as a function of fastener type. This table also identifies the test specimens which were protectively coated as well as the specimens which were subjected to fatigue loadings. The twenty unprotected baseline samples, ten using A-286 CRES fasteners and ten using titanium fasteners, were fabricated by installing the fasteners in the uncoated graphite/epoxy and aluminum plates. These specimens were not fatigue tested. They represent the baseline material response which the protectively coated specimens were evaluated against. The protected specimens consisted of: (1) chromic acid anodized aluminum alloy with two coats of epoxy primer (MIL-P-23377); (2) composite skin structure assembled with sealant (MIL-S-83430) (and epoxy Hysol EA 9300 with chopped fiberglass applied to the composite) in faying surface; (3) fasteners were wet-installed with MIL-S-83430 sealant, and (4) the exterior surface of the composite skin structure was coated with one coat of epoxy primer (MIL-P-23377) and two coats of exterior polyurethane (MIL-C-83286). Selected specimens were painted such that the edges of the composite plates were left uncoated. This was done to determine the effect of quality control on the corrosion response of the aluminum structure.

Of the seventy test specimens which were protectively coated, fifty were subjected to fatigue loading at a predetermined period during the test. Twenty-five of these specimens were fabricated using A-286 CRES fasteners and the remaining used titanium fasteners. Twenty of the protectively coated specimens were not

fatigue tested at all. These specimens were only exposed to the accelerated corrosion environment, therefore providing a basis on which to evaluate the effect of fatigue loads on the corrosion response of graphite/epoxy - aluminum structure.

2. TEST PROCEDURES

The testing sequence consisted of corrosive environment exposure, fatigue cycling and a second corrosive environment.

The exposure cycle consisted of the following:

a. The specimens were exposed to a salt spray for a 24-hour period in accordance with ASTM B117-73 ($95^{\circ}F$, 5 $\pm 1\%$ by weight of sodium chloride).

b. The specimens were rinsed and then exposed to high-humidity, high temperature for 120 hours (5 days) in accordance with ASTM D2247 ($120^{\circ} \pm 2^{\circ}F$, 100% RH).

c. The specimens were permitted to air dry for 24 hours and returned to salt spray exposure.

(1) This sequence was repeated 12 times (i.e. twelve weeks) and then the specimens were cyclically loaded.

(2) The fatigue cycling consisted of the following constant amplitude fatigue spectra:

a. 1,000 cycles with 1,200 pounds tensile load (40% ultimate stress) and 100 pounds compression loading at 2.5 Hz.

b. 100 cycles with 2,000 pounds tensile load (66% ultimate stress) and 100 pounds compressive loading at 2.5 Hz.

This fatigue sequence was repeated 22 times (24,200 cycles).

3. SPECIMEN EVALUATION

After two accelerated corrosive environmental exposures and one fatigue cycling, the specimens were evaluated to determine the extent of corrosion. The principal evaluation method used to determine the extent of corrosion was optical microscopy. A portion of the specimens were sectioned along the axis of the fasteners, through the aluminum and composite, to determine the extent of corrosion on or around the fastener and at the joint where the two composite portions of the specimen butt together. A full discussion of these results is presented in the following section.

SECTION III

RESULTS AND DISCUSSION

The evaluation of the composite/aluminum lap-joint samples after corrosion and fatigue testing will be discussed for both the unprotected and protected samples.

1. BASELINE-UNPROTECTED SAMPLES

After a relatively short exposure time, the uncoated samples started to exhibit localized pitting along the edge of the aluminum plates. In all twenty cases, the aluminum was severely attacked at the edge where the two composite sections butt together. During the first twelve week corrosion testing period, corrosion and salt products began building up in the faying surface of the composite and aluminum section causing bending of the aluminum plate. These by-products can be seen in Figure 4 and Figure 5, C and D. The by-products resemble a fine whitish-gray salt wedged into the faying surface of the structure. After the second twelve week exposure the continued buildup of corrosion and salt products resulted in plastic deformation of the aluminum plate and substantial localized deformation of the graphite/epoxy composite.

a. A-286 CRES Fasteners

The effect of the exposure to two corrosion cycles without the fatigue test sequence for the unprotected samples is shown in Figure 4 for the joints with A-286 CRES fasteners. The front and back of the test sample and two edge views are shown. In the front view (Figure 4a), the formation of red rust on the

A-286 CRES fastener around the center pin can be seen. In the view of the back of the sample (Figure 4b), the generalized corrosion attack on the surface of the aluminum and the more concentrated attack along the edge and adjacent to the fastener may be seen. The views of the joint area from either edge are shown in Figures 4c and 4d. The buildup of the corrosion and salt products between the composite and the aluminum plate may be seen. The deformation of the aluminum and the composite is quite evident.

b. Titanium Fasteners

The effect of the corrosive exposure on the unprotected composite joints with titanium fasteners is shown in Figure 5. In the front view (Figure 5a), the titanium fastener, as expected, showed little effect of the corrosive exposure. In the rear view (Figure 5b), the generalized corrosion of the aluminum may be seen. In the edge view (Figures 5c and 5d) the severe pitting of the edge of the aluminum may be seen. The buildup of the corrosion and salt products under the composite, in the area where the composite portions of the sample butt together, caused the ends of the graphite epoxy composite to bow up.

c. Tensile Testing

Three as-fabricated specimens were loaded in tension to failure, the failure load was approximately 8000 pounds. Each of these specimens failed in the composite in a line across the fasteners as a result of outward bending by the specimen under the load. This load response was anticipated due to the struc-

tural configuration used in the design of these test specimens. As stated earlier in this report this design configuration was chosen to insure adequate fatiguing of the protective coatings and sealants. The structural testing was not a primary objective of this program, therefore, limited effort was expended in obtaining this type of data.

After corrosive exposure and fatigue testing, three unprotected samples were tensile tested, to determine if there were any gross changes in the failure load response. The three samples did fail at a slightly lower load, but in the same manner as the as-fabricated samples. This reduced failure load was attributed to the bowing of the sample resulting from the buildup of the corrosion and salt products, as previously described. The bowing resulted in an increased bending moment in the joint in addition to the moment induced by the tensile load during static testing. Because of the complexities of testing bowed samples, and the fact that the sample design configuration does not lend itself to the generation of good static strength test results, the reduced failure loads cannot be attributed to the degradation of the composite or aluminum due to the corrosive exposure and fatigue testing. It was therefore dropped from the remaining portions of the project.

2. PROTECTED SAMPLES

In this section of the report the corrosion response of the protected samples which were not subjected to fatigue cycling

will be presented. This will be followed by the data collected on the protected samples which were subjected to both fatigue and corrosive environment. Photographs of the samples were prepared for all the protected samples after undergoing testing. In addition a portion of the samples were sectioned through the fasteners parallel to the sample axis where the two composite portions overlap the aluminum and butt together.

The third portion of this section will present a comparison of the two types of samples and discuss the major difference in their response to the corrosive environment.

In general, the protected samples exhibited dramatically improved corrosion resistance compared to the unprotected samples; however, several possible problem areas with the protected samples were identified. These problem areas will be discussed in detail in the following paragraphs:

a. Corrosive Environment Exposure Only-Results

As discussed earlier, the most critical area of this type structure is in and around the substructure fastener hole. If corrosion pitting occurs, in either the fastener or around the periphery of the fastener hole, then a point of stress concentration is established. Under continual operational use these pits could initiate a crack and result in premature structural failure. Therefore when the use of dissimilar metals such as graphite and aluminum is decided upon, it is imperative that these materials be kept electrolytically isolated from each other. This is presently being accomplished by the use of paints, primers, and sealants. If these protective systems fail

then the structure becomes vulnerable to corrosive deterioration. This portion of the program studied the degree to which the protective coatings were able to limit or prevent corrosion from occurring in the fastener hole area. In addition the butt joint area was also evaluated along with the faying surface bondline.

As shown in Table 1 there were a total of twenty test samples which were protectively coated and exposed to two accelerated corrosion cycles. Ten of the twenty samples were assembled using A-286 CRES fasteners while the remaining samples used titanium fasteners. Three samples of each type were cut into along the centerline of the fasteners. Photos were taken of the fastener hole, faying surface bondline, and butt joint. Figure 6 presents a collection of photos, from six different samples, of one fastener and the fastener hole area from each sample. These six samples were randomly chosen from the twenty protected samples which underwent accelerated corrosion testing.

In general, the fastener holes appear to be totally free of corrosion. The faying surface sealants adjacent to the fastener hole appear to be in good shape. Sealant is still visible in the countersunk area between the hole surface and the head of the fasteners. The dark area, which can be seen on the composite, adjacent to the fastener hole, on samples A-81, A-82, A-126, A-128, A-129, is a result of poor drilling technique. A discrepancy appearing in the photos in Figure 6 is the peeling of the top coat on the fastener heads. This did not occur during testing but was a result of the cutting process during pre-

paration for inspection. As can be seen in Figure 7, all of the top coats appear to be well intact except for a few chips.

Note, on samples A-82 and A-84 some signs of red rust are beginning to appear around the center pin of some of the CRES A-286 fasteners. This appears to result from either the paint chipping or the paint not covering a sharp corner on the fastener head.

The A-286 blind fastener, fabricated by Huck Manufacturing Company, uses a crimping action at the tail of the fastener to hold the structure together, hence requiring no fastener collar. This crimping action is applied by pulling the center pin up through the center of the fastener crimping the tail of the fastener and then locking the center pin into place, all in the same action. This is all accomplished by the pulling, then fracturing, of a serrated pin which is an integral part of the fastener center pin. Figure 8 illustrates the sequence of events during the installation of this type fastener. As a result of this technique a rough fracture surface is formed. This fracture surface is difficult to adequately cover because of all the sharp corners and peaks. This produces an ideal area for the initiation of corrosion, which is evident in Figure 7. However, except for the unsightly appearance of the red rust there were no adverse effects noted during program testing.

Figure 9 is an enlarged view of the same six samples that were shown in Figure 6. In this series of photos the

fastener hole and butt joint are both visible. Again, let it be emphasized that these six samples were chosen at random. Of the six samples, all six show little to no squeeze-out of sealant between the ends of the composite portion of the structure. As a result of this, three of the samples show slight to moderate pitting corrosion, the whitish area at the base of the joint, in this area of the structure.

Any faying surface disbond, samples A-81, A-84, A-128 and A-129, is a result of torque-up of the sample during fastener installation and lack of adequate faying surface sealant. This brings to light the importance of having proper sealant squeeze-out if the structure is to ever be protected from corrosion.

Up to this point the defects which are similar on the two different types of samples have been discussed. The following is a discussion of defects which were unique to each design. A defect that was observed on just a single design was that of pitting around the crimped region of the A-286 fasteners. It can be seen in both Figure 6 and Figure 9 that there was an advanced stage of corrosion pitting in this area on sample A-81 and A-84. This same corrosion response was observed on practically all protected samples which used A-286 fasteners. Some possible reasons for this lie in the fact that 1) fastener holes in the substructure were drilled after the structure was anodized and primered, a typical fabrication process used by industry, which may allow for surface damage to occur during drilling, 2) microcracking of the primer resulting from loads

applied by the fastener during crimping, 3) no primer coating is 100% perfect, and 4) aluminum is very anodic to steel, thereby resulting in a large electrolytic dissimilarity producing the necessary driving force for the initiation of galvanic corrosion. Couple these possibilities with the fact that this area is ideally designed to hold salt and moisture, even after the sample is rinsed off, then this frequent occurrence of corrosion in this area is not surprising. Few such observations were seen on the sample which used titanium fasteners, probably because sealant was able to be squeezed out between the washers and aluminum structure during assembly. This would result in a well sealed interface and no damage to the protective primer on the aluminum. The above observations are better illustrated in Figure 9. This figure shows the substructure of all six samples, before they were cut into. Note the lack of corrosion products at the base of the titanium fasteners while every A-286 fastener shows some degree of corrosion pitting at and around the base of the fastener, at the substructure-fastener interface.

Another observation which can be made from Figure 10 is the presence of pitting corrosion on the aluminum collars used with the titanium fasteners. This was observed on every sample using titanium fasteners. The reason for this is due to the large electrolytic dissimilarity between titanium and aluminum. This dissimilarity produced a galvanic couple resulting in corrosion pitting.

Another significant observation made was the occurrence of moderate to severe pitting corrosion along the edge of the aluminum substructure. In this area it was obvious that the aluminum was going to be in very close proximity to graphite fiber ends, which were exposed along the end edge of the composite structure. It was felt at the start of this program that such an area as this would be very vulnerable to corrosion when subjected to a corrosive environment. It therefore was decided that the edges of the composite structure, on some of the samples, should be painted so that a comparison could be made. Figure 11 presents photos of the edge of the six samples which were selected from this group. It can be seen that all six samples experienced some degree of pitting along the edge of the aluminum. This was typical of all the samples tested. As can be seen A-129 was one of the samples which had the edge of the composite painted. This reduced, but did not prevent, corrosion from occurring. Another significant point to consider is the fact that the aluminum alloy used was 2124-T851, which is supposed to be a more corrosive resistant aluminum alloy than the 2024 series. Also the substructure was chromic acid anodized and covered with two coats of epoxy primer (MIL-P-23377). Such protective steps only reduce the chance of corrosion occurring. However, no paint, primer, or anodize layer can be 100% perfect; therefore, the chances of totally preventing corrosion are slim.

b. Corrosive Environment and Fatigue Cycling-Results

The principal objective of this program was to assess the corrosion response of the structure in and around fastener

holes after the structure has been exposed to cyclic loading and accelerated corrosive environmental conditions. This section of the report will present test results from the fifty samples which were tested under these conditions.

The test samples used in this segment of the program were fabricated of the same materials as the previous samples and protected using the same coatings, sealants and primers. Twenty-five of the samples used A-286 CRES fasteners; the remaining used titanium fasteners.

As discussed earlier, the samples were exposed to an accelerated environment, then cyclically loaded using a constant amplitude fatigue spectrum, followed by a second accelerated corrosion exposure cycle.

Six samples were chosen at random for detail study. The six samples, shown in Figure 12, were samples A-166, A-174, A-183, A-204, A-214, and A-220. Three were assembled using A-286 CRES fasteners and the remaining three used titanium fasteners. Again, the primary area of interest was the fastener hole area. However, the faying surface bondline, butt joint and exterior of the samples were studied and will be discussed in this section.

As can be seen in Figure 12, the upper surface of these samples, typical of all fifty samples, appear in good shape, except for the red rust products on some of the A-286 fasteners. The top coat appeared to have withstood the structural loading without cracking or peeling.

Figure 13 is a series of macrographs of a fastener hole from each of the six samples. The material response of these

samples, in this area, was identical to that seen in the samples which underwent accelerated corrosion testing only. It appears that the fatigue loading did not produce any cracks or deterioration in the protective coatings and sealants around the fasteners. Of course this is a function of load level and if the applied loads had been higher the response may have been different.

As noted before, these samples also showed severe pitting at the location of crimping on the samples using A-286 fasteners. Also, as noted before, the aluminum collars used on the titanium fasteners show signs of severe pitting. Figure 14 presents a series of photos which show the backside of these six samples showing these areas of corrosion. Figure 15 shows enlarged views of the same fasteners shown in Figure 13 but the butt joint area and faying surface bondline are also shown. As can be seen in these photos, samples A-174, A-183, A-204, A-214, and A-220 show that there was more than adequate squeeze-out of sealant in the butt joint area. However, sample A-166 had very little squeeze-out and, as can be seen, all samples show no signs of corrosion in this area.

Note the large cracks appearing in the sealant in the joint area. These cracks appear to have resulted due to sealant curing then aggravated by the structural loads which were applied during fatigue cycling. This is evident by the smaller cracks in the sealant adjacent to the aluminum substructure and the corner of the composite skin structure. This appears on all six samples

and if left undetected on actual aircraft structure could result in increasing the structure's vulnerability to corrosion. The sealant (MIL-S-83430) is the type presently being used on the faying surface on many aircraft which have composite-aluminum structure.

Figures 16 and 17 show a series of photos comparing the samples which were assembled in the same manner but tested under the two different conditions. Samples A-81, A-82, A-84, A-126, A-128, and A-129 were not fatigue cycled, the other samples did undergo cyclic loading. These photos show the similar response of each group of samples regardless of whether the samples underwent cyclic loading or not.

Figure 18 is a series of macrographs showing the edges of the six samples A-166, A-174, A-183, -204, -214, and A-220. As can be seen in these photos, the edges of the composite structure were covered with polyurethane top coat. However, this did not prevent the occurrence of corrosion. The corrosion response of this portion of these test samples was very similar to that of the samples which did not undergo load cycling.

The corrosion response of these twelve samples was remarkably similar, regardless of whether the samples underwent cyclic loading or not. It is felt that these results represents a good summary of the response of all seventy samples because of the random selection process used and the resulting similarities between all of these samples.

SECTION IV

CONCLUSIONS

The evaluation of the graphite/epoxy joint fastened to an aluminum alloy plate with either A-286 CRES or titanium fasteners subjected to accelerated corrosion and fatigue testing resulted in the following conclusions.

1. The unprotected samples with either A-286 CRES or titanium fasteners experienced severe galvanic corrosion of the aluminum plate. The formation of the corrosion products between the composite and the aluminum alloy plate resulted in gross deformation of both the aluminum alloy and the graphite-epoxy composite.

2. The protected samples with the finishing system similar to that used on the F-16 aircraft represented a significant improvement in resistance to corrosion compared to the unprotected samples. The accelerated testing of the protected samples indicated the following problem areas:

    a. The area where the composite skin structures butt together forming the lap joint, showed up as an area of vulnerability. Samples which did not have proper protection in this area showed signs of galvanic corrosion, this response would be expected due to the ability of this area to retain moisture and salt products. Another observation made was the voids in the sealant due to its curing. This would make a structure even more vulnerable to corrosion because once moisture was able to get into such an area it would be almost impossible to get out.

Secondly, the sealant exhibited signs of being very brittle once it had dried. This was noted by the small cracks beneath the larger voids formed by the sealant when it dried. These small cracks would provide direct exposure of the aluminum structure to water, or any trapped fluid that could also be in contact with graphite fibers. Such a situation would open the door to setting up a galvanic couple.

b. When the composite was not painted on the edge, severe pitting of the primed aluminum alloy would occur. By painting the edges of the composite the severity of the pitting was reduced, but not completely removed.

c. The A-286 CRES fasteners corroded around the center pin of the fasteners on the front side of the composite causing rust stains to form on the face of the painted composite. On the rear side of the joint where the crimped portion of the A-286 CRES fastener contacted the aluminum, galvanic and crevice corrosion of the aluminum occurred.

d. The titanium fasteners performed better than the A-286 fasteners but a moderate to severe galvanic corrosion problem did appear on the aluminum collars used with these fasteners.

3. When comparing those samples exposed only to corrosion testing with samples exposed to both corrosion and fatigue testing no difference in the corrosion behavior could be determined.

SECTION V

RECOMMENDATIONS

The following recommendations are based on the conclusions drawn from accelerated and very harsh test conditions. If correlation exists between these accelerated tests and service conditions, these recommendations may result in improved long-term corrosion resistance of mechanically fastened joints.

1. Special care must be taken to ensure that the area is properly sealed where two composites butt together or a composite terminates in a mechanically fastened joint. This sealing is required to prevent the entrance of water and the resultant galvanic or crevice corrosion.

2. The composite should be painted on the edge prior to installation in order to prevent attack of the aluminum understructures. The purpose of coating the composite is to paint the cathodes in order to ensure a large anode to cathode ratio and reduce the corrosion current density if a defect is present in the aluminum coating.

3. Further testing should be conducted using a sample design which would lend itself to structural fatigue testing. By doing this the degradation of the structure's strength, resulting from corrosion, could be determined.

REFERENCES

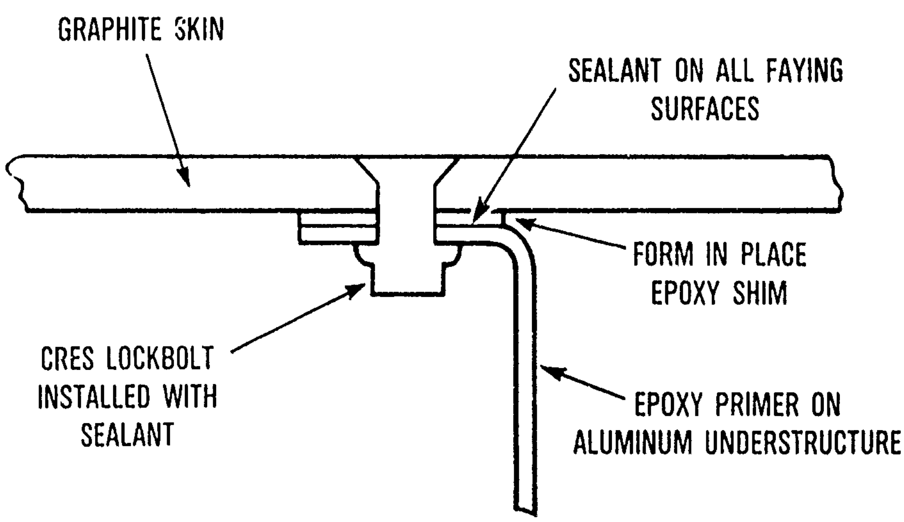
1. D.G. Treadway, Corrosion Control at Graphite/Epoxy-Aluminum and Titanium Interfaces, General Dynamics, Air Force Materials Laboratory, Wright- Patterson Air Force Base, Ohio 45433, AFML-TR-74-150, 1974.

2. S.G. Lee and B.A. Miller, The Effect of Graphite/Epoxy Composites on the Galvanic Corrosion of Aerospace Alloys, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, AFML-TR-76-121, 1976.

3. D.E. Prince, Corrosion Behavior of Metal Fasteners in Graphite/Epoxy Composites, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, AFML-TR-75-53, 1975.

SPECIMEN NUMBERS	PROTECTIVE COATINGS USED	FATIGUE LOADED	FASTENER MATERIAL		NO. OF SPECIMENS
			A-286	Ti	
A 1-10	NONE	NO	X		10
A 41-50	NONE	NO		X	10
A 81-90	YES	NO	X		10
A 121-130	YES	NO		X	10
A 161-185	YES	YES	X		25
A 201-225	YES	YES		X	25

TABLE 1. TEST SAMPLE CONFIGURATIONS



- A-286 CRES AND TITANIUM FASTENERS WET INSTALLED WITH SEALANT
- LIQUID SHIM AND SEALANT ON GRAPHITE TO ALUMINUM FAYING SURFACES
- SEALANT ON UNDERSTRUCTURE FAYING SURFACES TO PREVENT ENTRANCE OF GRAPHITE DUST
- FIBERGLASS PLY ON INNER SURFACE OF COMPOSITE SKINS

Figure 1. Sketch of F-16 Aircraft Corrosion Protection Scheme

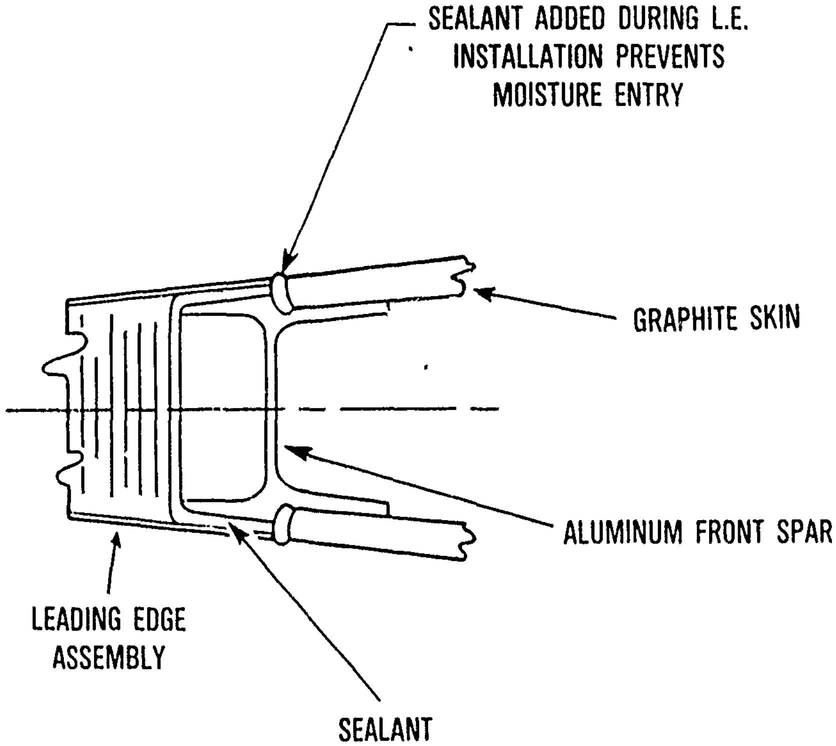
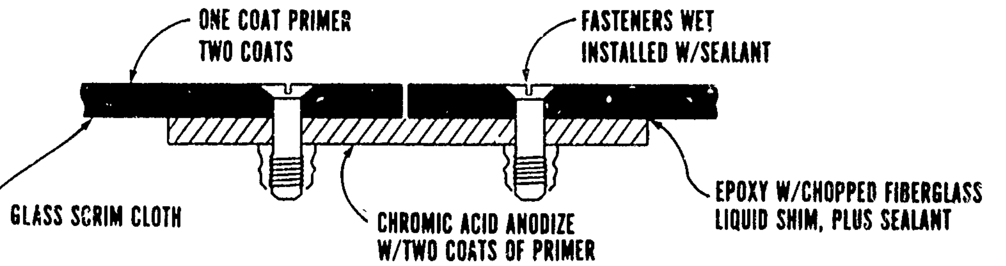
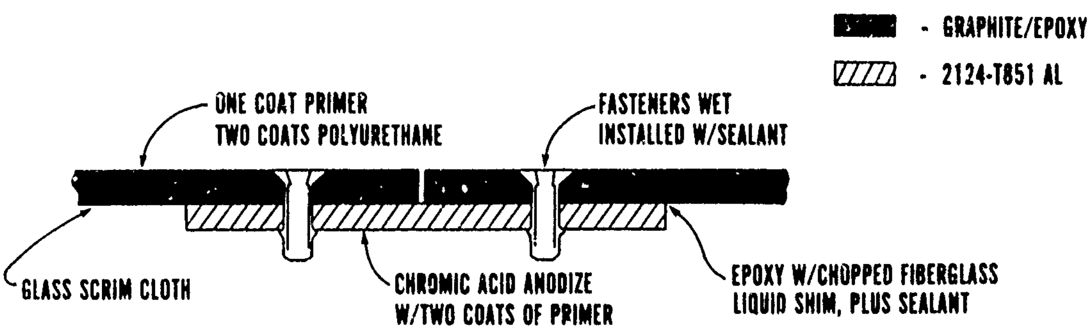


Figure 2. Leading Edge Installation to Prevent Moisture Entry to Front Spar-Skin Joint on the F-16 Aircraft Vertical Stabilizer

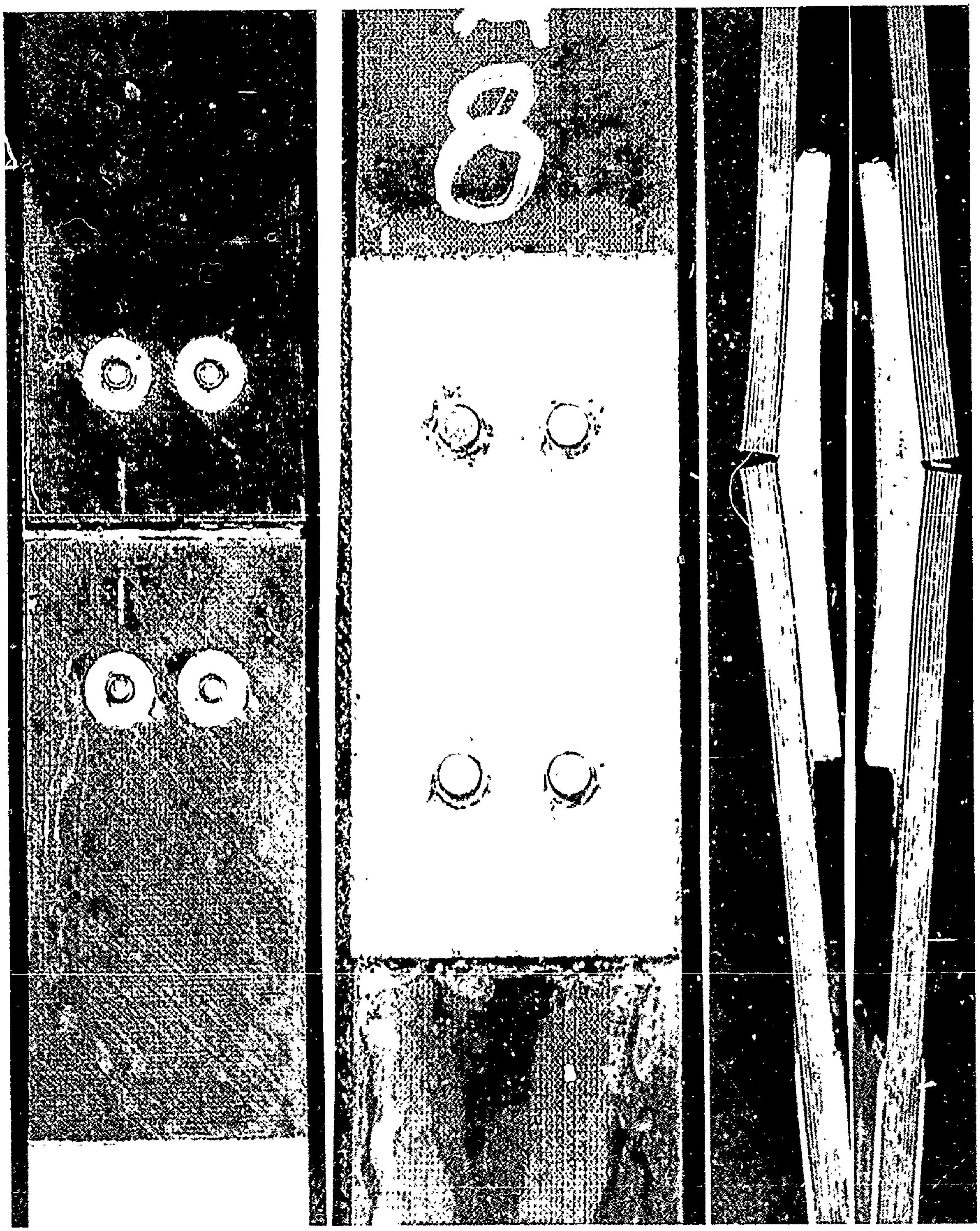


(NAS 1154V4 TITANIUM FASTENER SPECIMEN DESIGN)



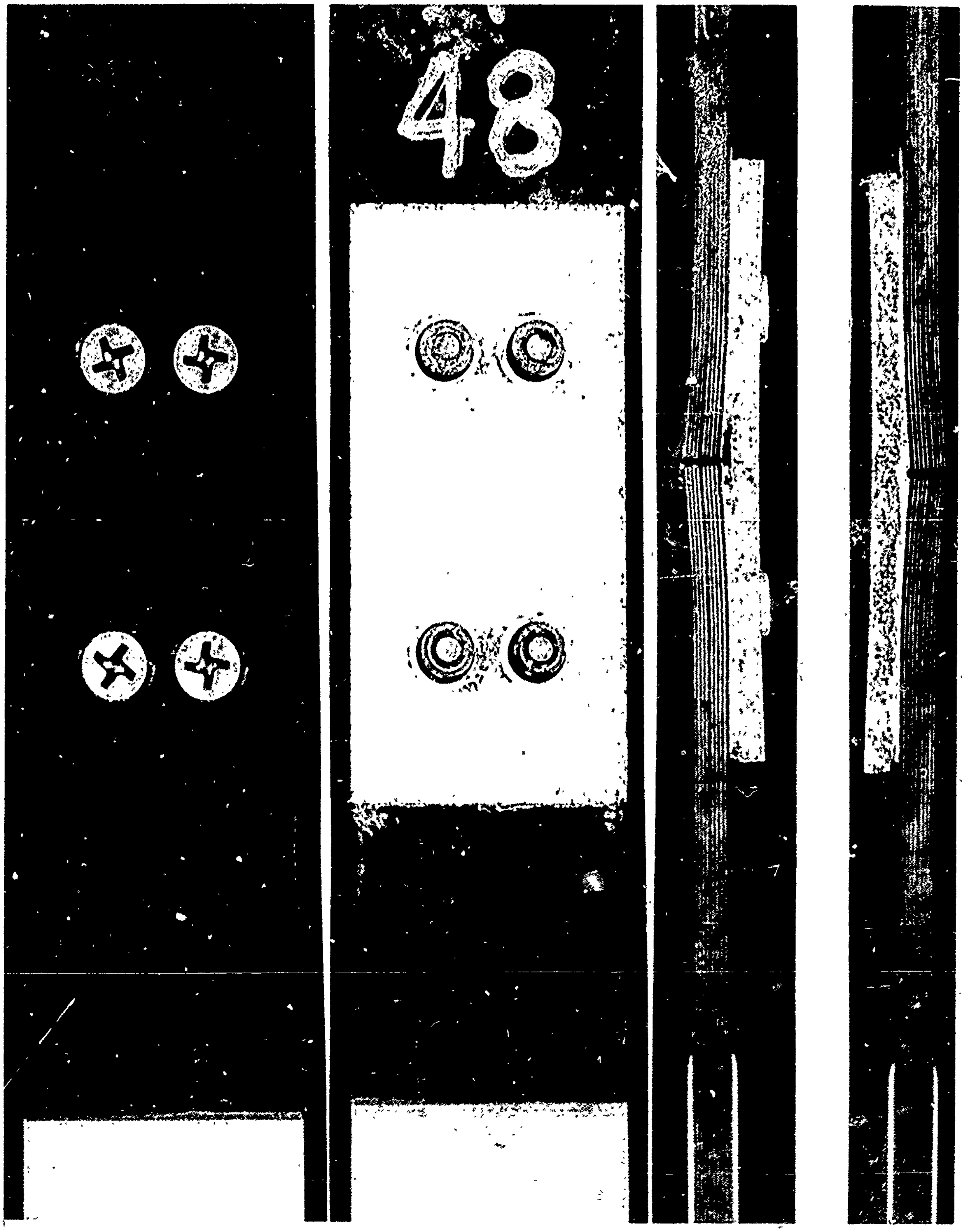
(A-286 CRES BLIND FASTENER SPECIMEN DESIGN)

Figure 3. Protected Lap-Joint Specimen Configuration



a. Front view b. Rear view c. edge 1 d. edge 2

Figure 4. Unprotected Graphite/Epoxy and Aluminum Alloy Lap-Joint Fastened with A-286 CRES Fasteners After Two Corrosion Cycles



a. Front view   b. Rear view   c. edge 1
d. edge 2

Figure 5. Unprotected Graphite/Epoxy and Aluminum Lap-Joint Fastened with Titanium Fasteners After Two Corrosion Cycles

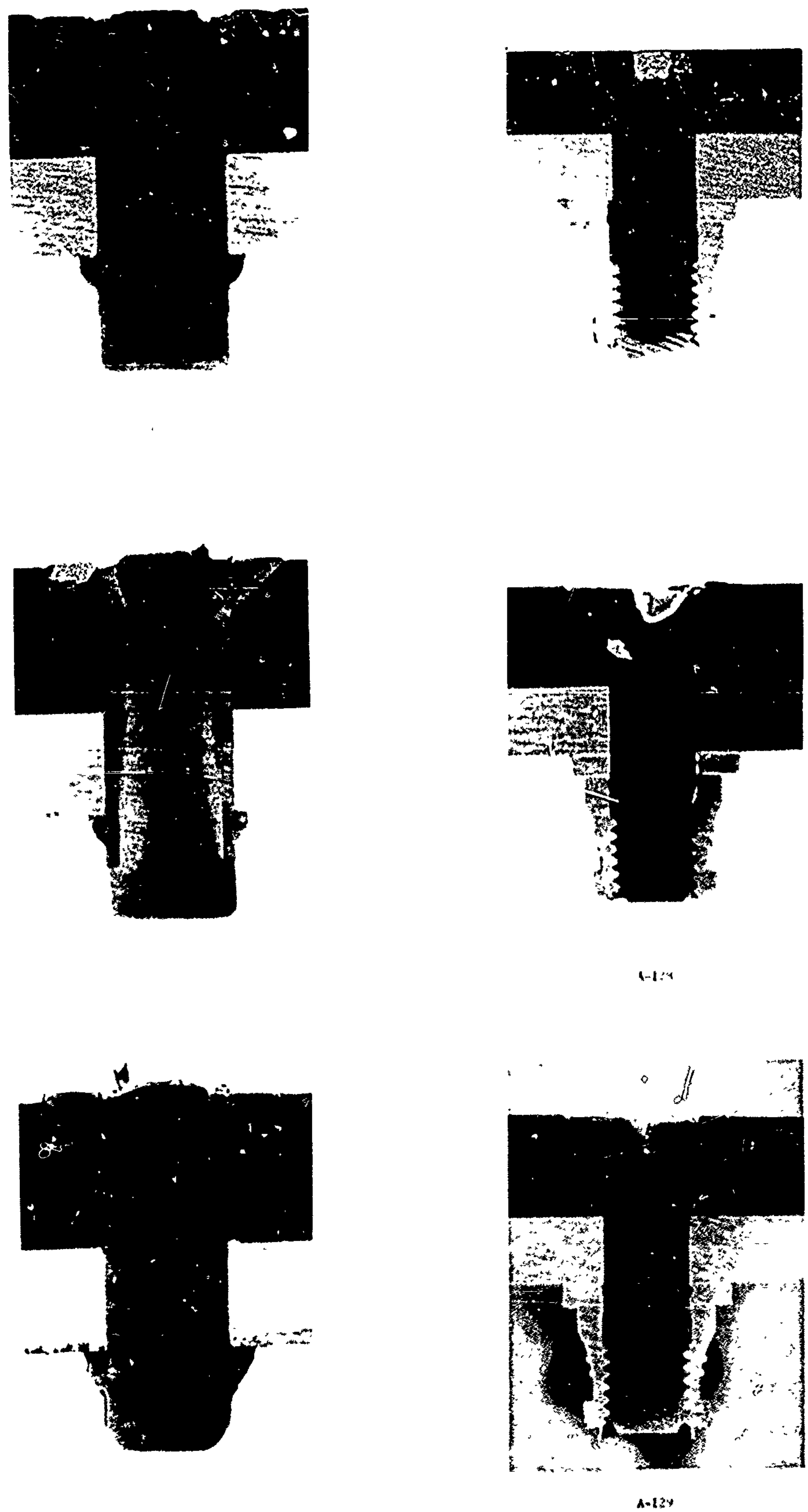


Figure 6. Protected Graphite Epoxy and Aluminum Samples, Fastener and Hole Condition After Two Accelerated Corrosion Cycles

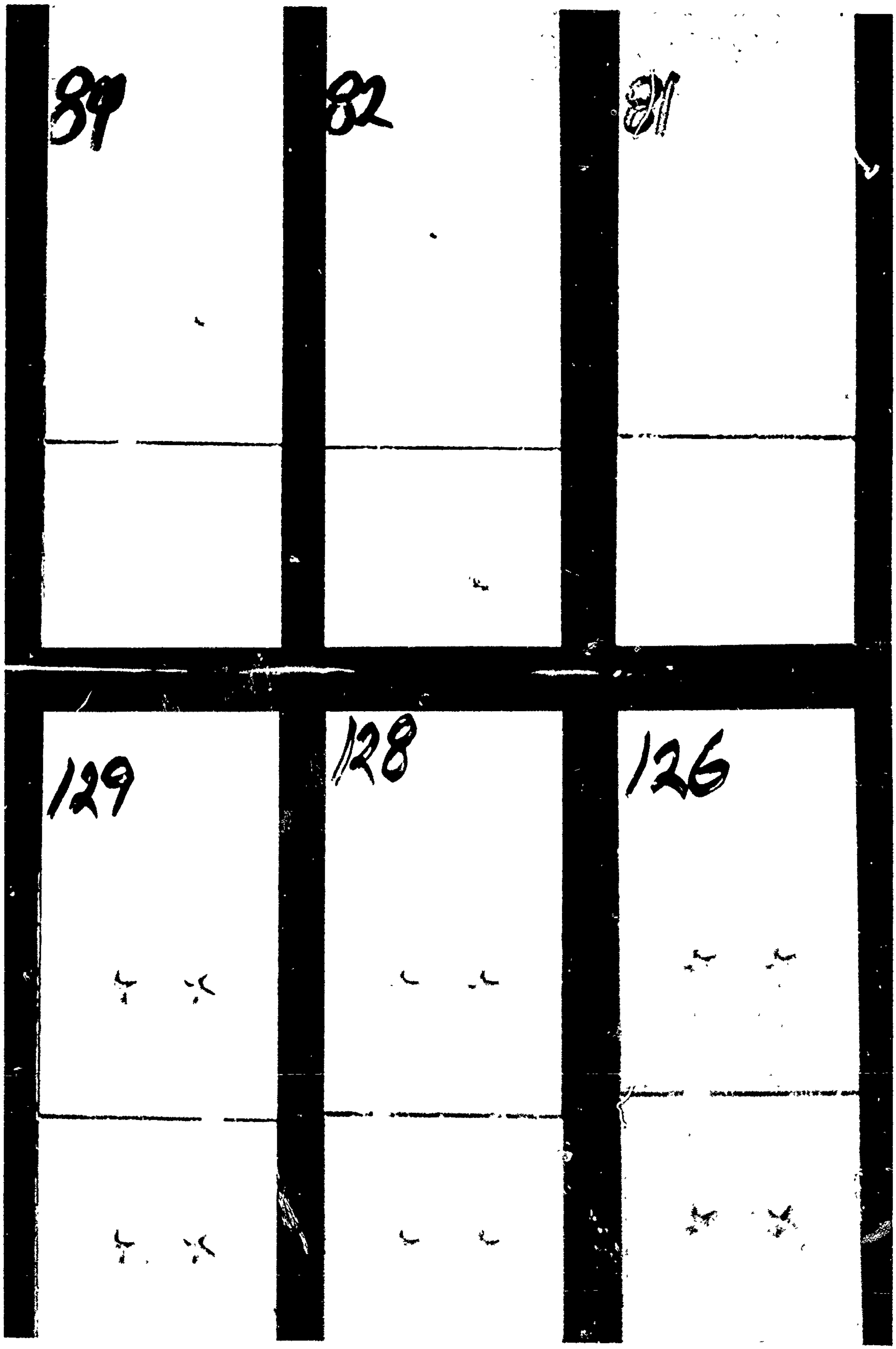
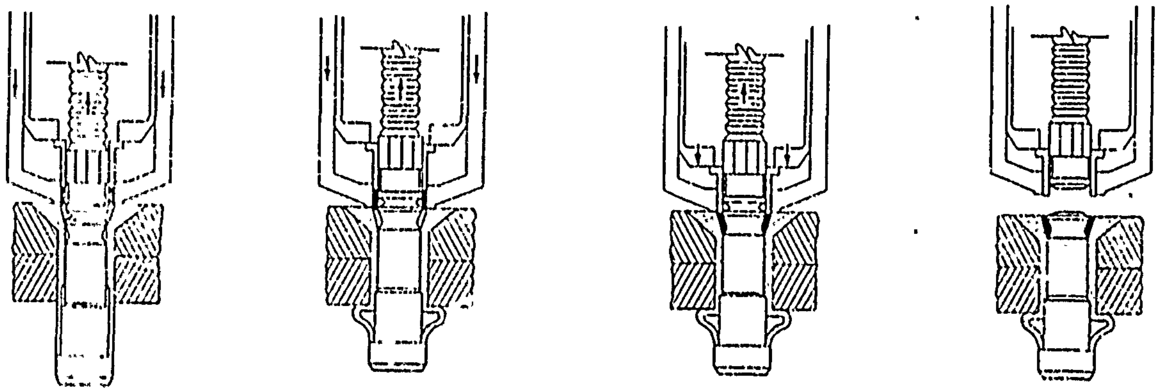


Figure 7. Protected Graphite/Epoxy and Aluminum Samples, Top Surface Condition Ater Two Accelerated Corrosion Cycles



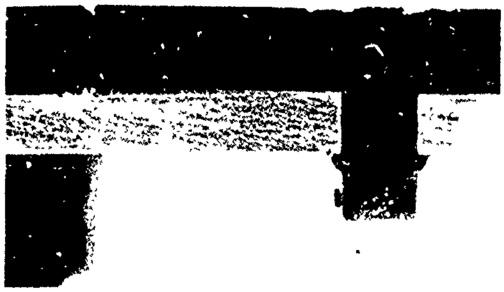
Step 1. During the initial part of the driving operation, the sleeve is squeezed be tween the head of the pin and the nose of the rivet tool.

Step 2. The head of the pin upsets the sleeve to form a strong, bulbed head on the blind side.

Step 3. When the blind head has been formed, the tool automatically forces the locking collar (at the pintail end of the sleeve) into the conical space be-tween the recess in the sleeve head and the locking groove in the pin. This locks the parts together perm-anently.

Step 4. Pin is broken off in tension at the break-neck groove, substantially flush with the head of the sleeve. There is no pro-jecting pin left to be cut off in a separate operation.

Figure 8. A-286 CRES Blind Fastener Installation Sequence



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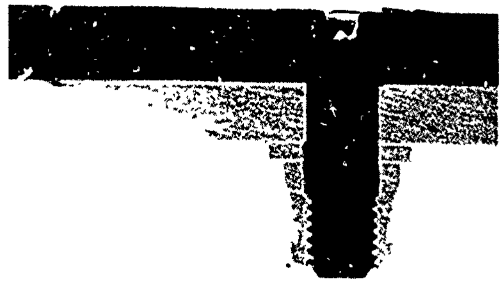

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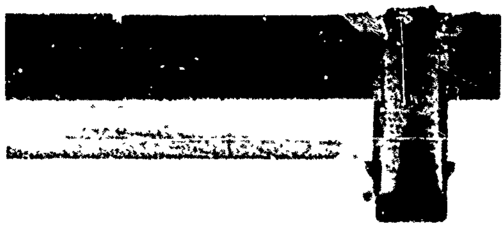

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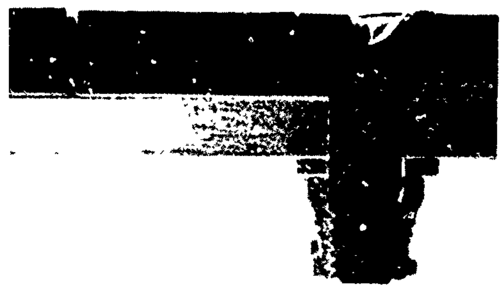

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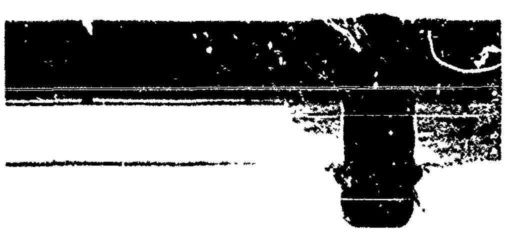

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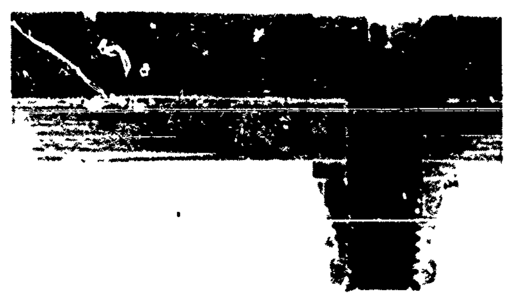


A-129

Figure 9. Protected Graphite/Epoxy and Aluminum Samples, Fastener and Butt Joint Conditions After Two Accelerated Corrosion Cycles

Figure 10. Protected Graphite/Epoxy Aluminum Samples, and Aluminum Structure Condition After Two Corrosion Cycles

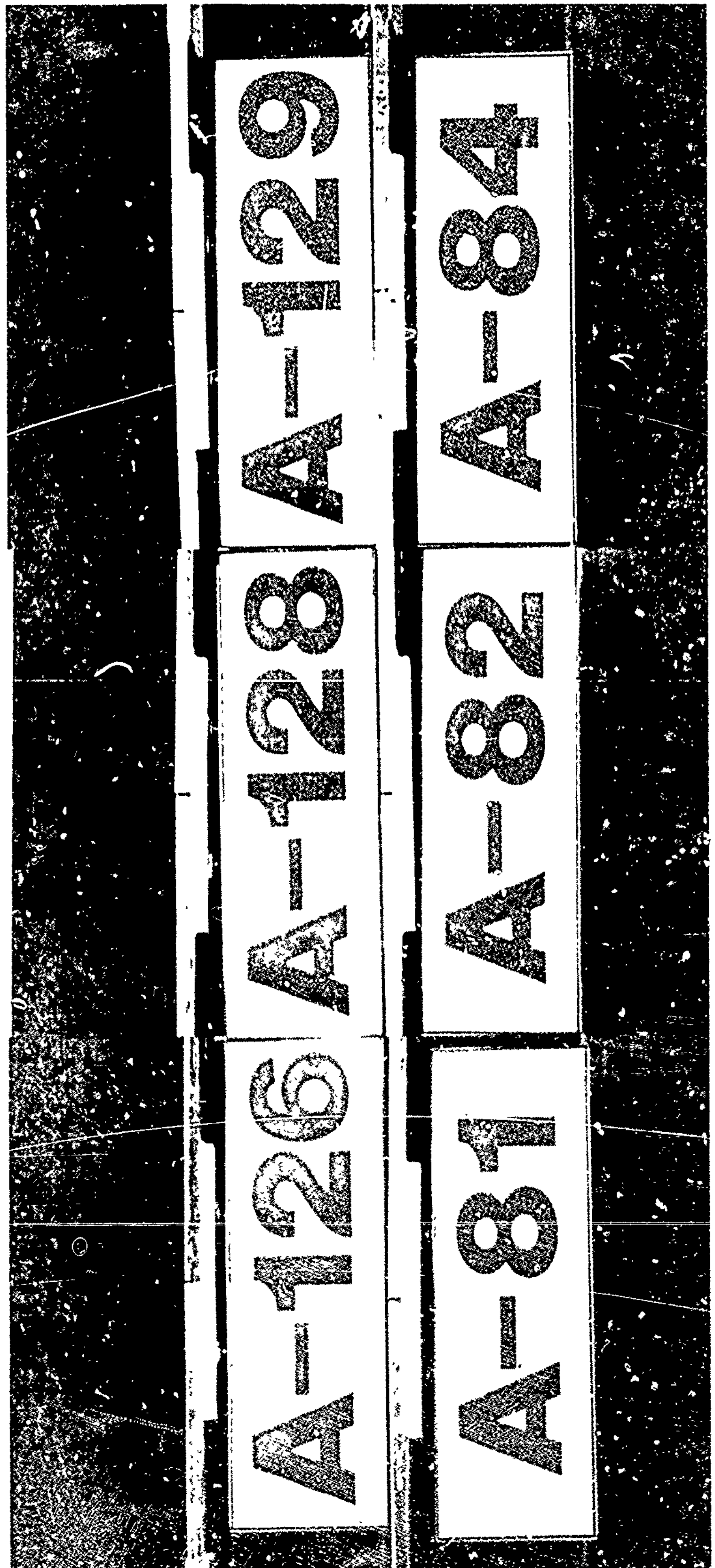


Figure 11. Protected Graphite/Epoxy and Aluminum Samples, Structure Edge Condition After Two Corrosion Cycles

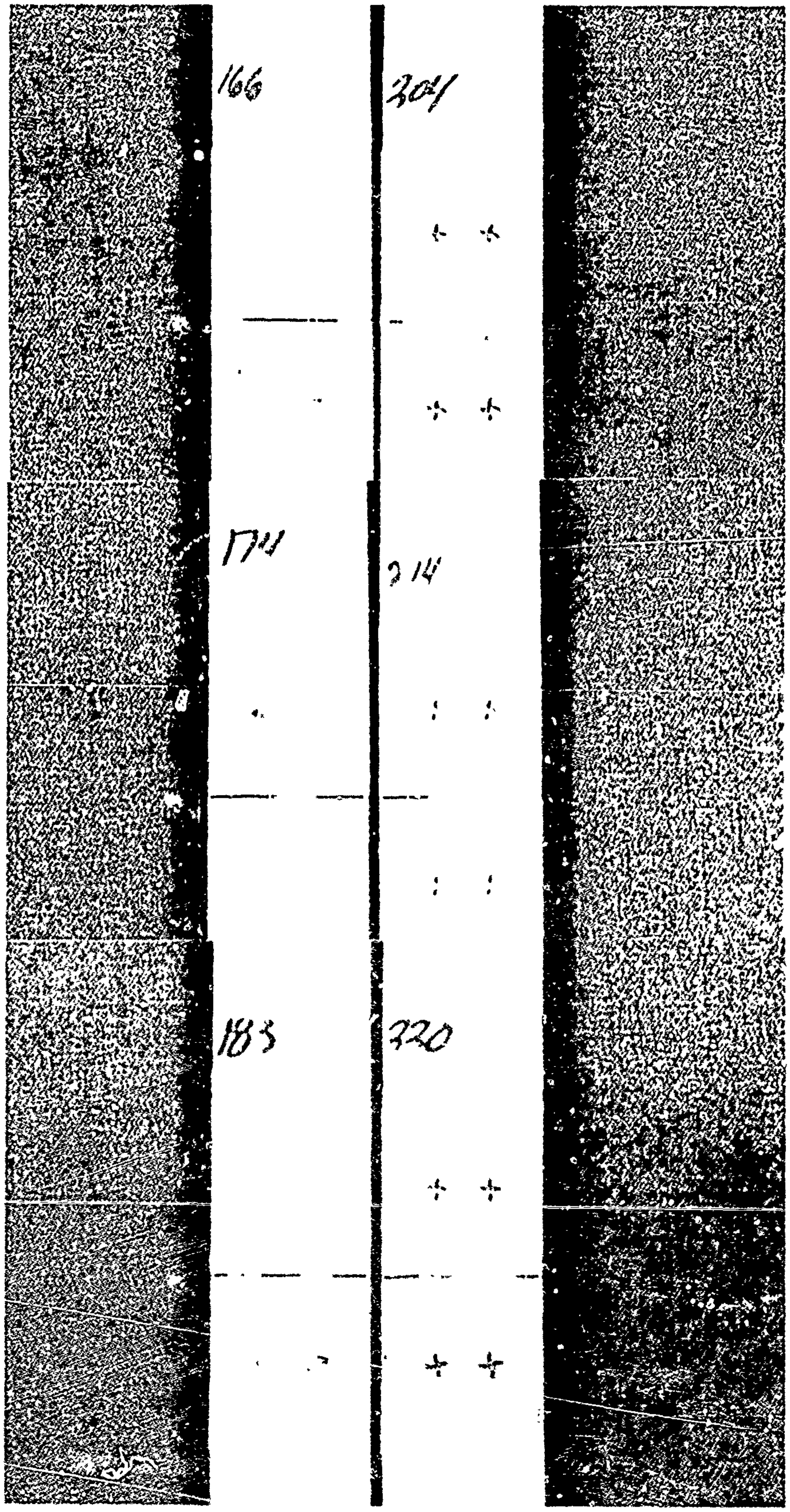


Figure 12. Protected Graphite/Epoxy and Aluminum Samples, Top Surface Condition After Two Accelerated Corrosion Cycles and One Fatigue Cycle

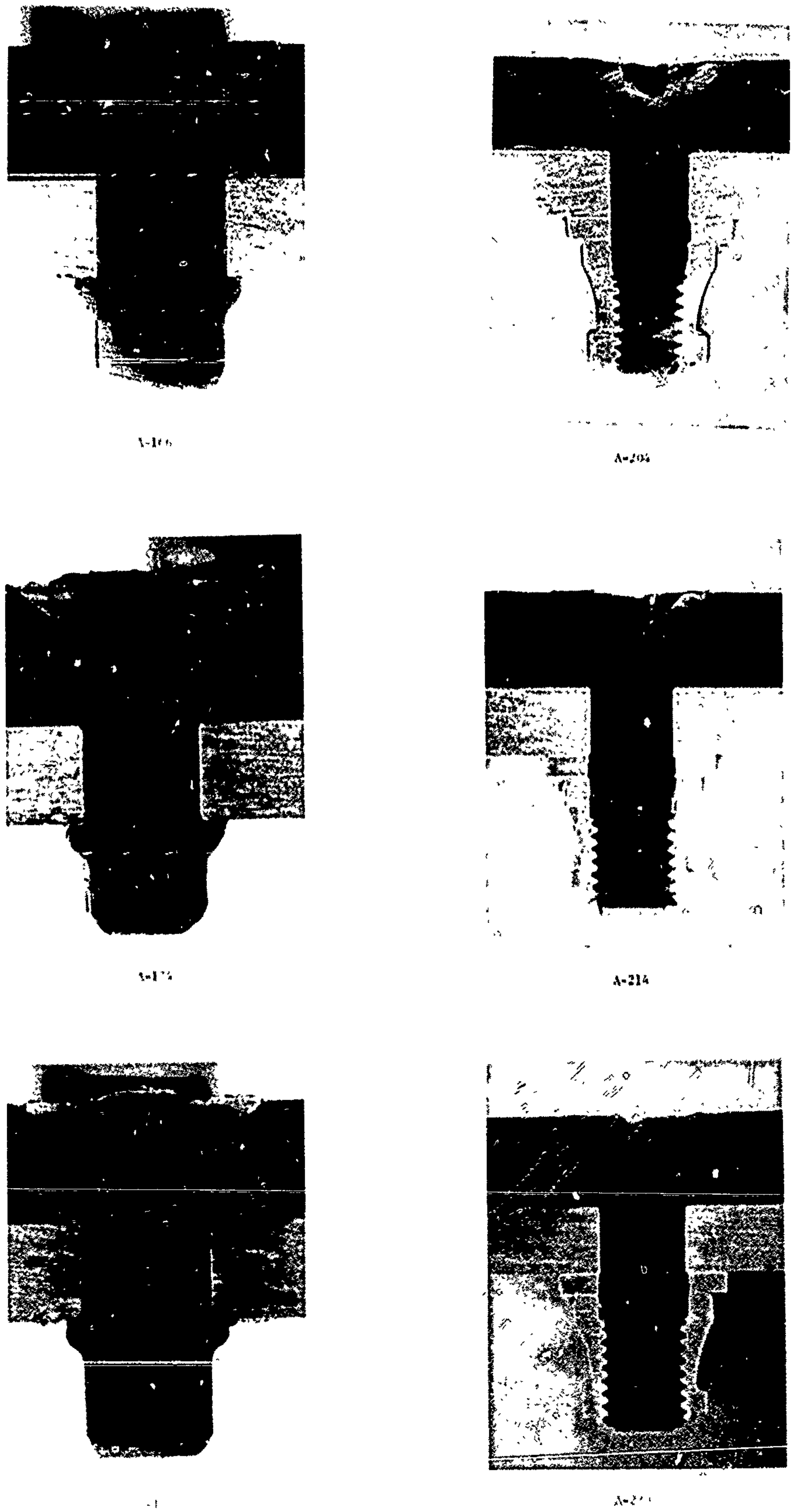


Figure 13. Protected Graphite/Epoxy and Aluminum Samples, Fastener and Hole Condition After Two Accelerated Corrosion Cycles and One Fatigue Cycle

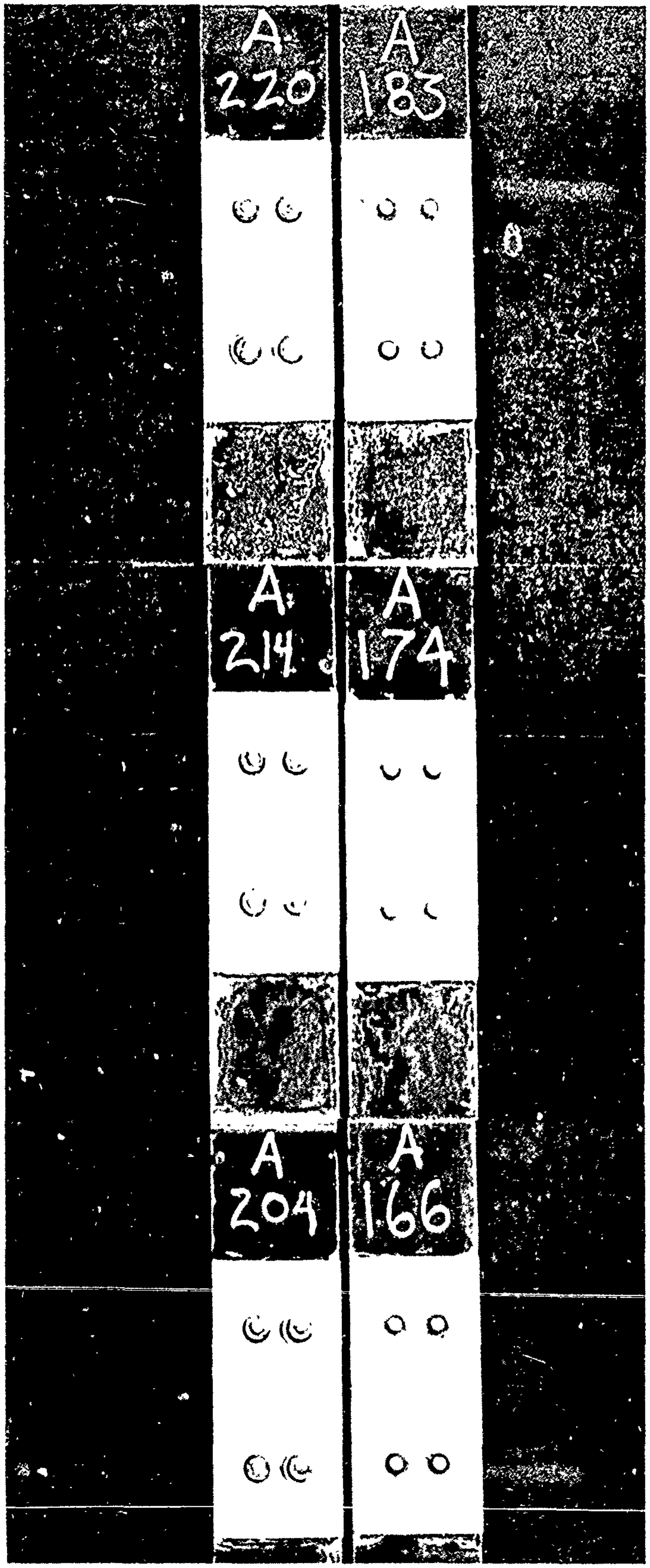


Figure 14. Protected Graphite/Epoxy and Aluminum Samples, Aluminum Structure Condition After Two Corrosion Cycles and One Fatigue Cycle

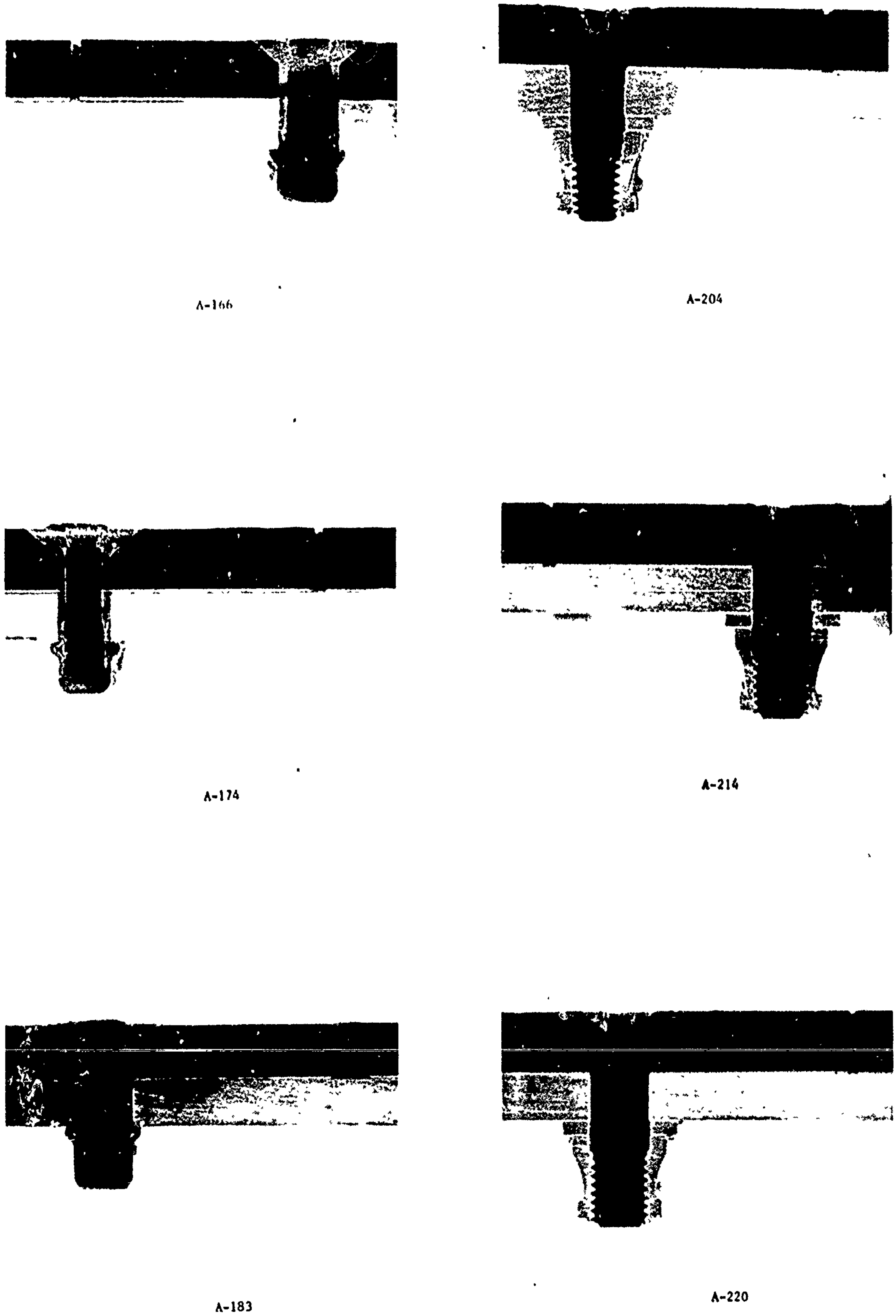
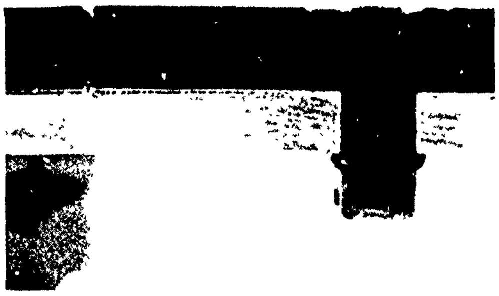


Figure 15. Protected Graphite/Epoxy and Aluminum Samples, Fastener and Butt Joint Condition After Two Accelerated Corrosion Cycles and One Fatigue Cycle



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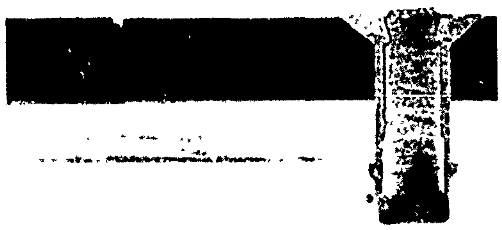

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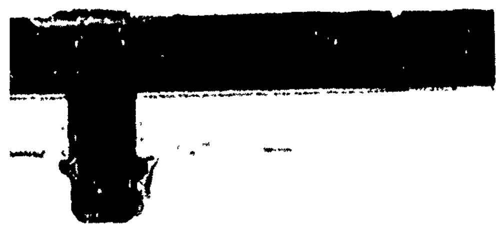

A-174

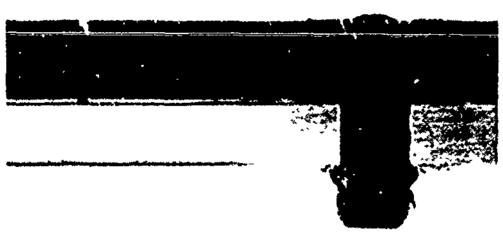

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Figure 16. Test Sample Comparison, A-286 CRES Fastener and Butt Joint Condition

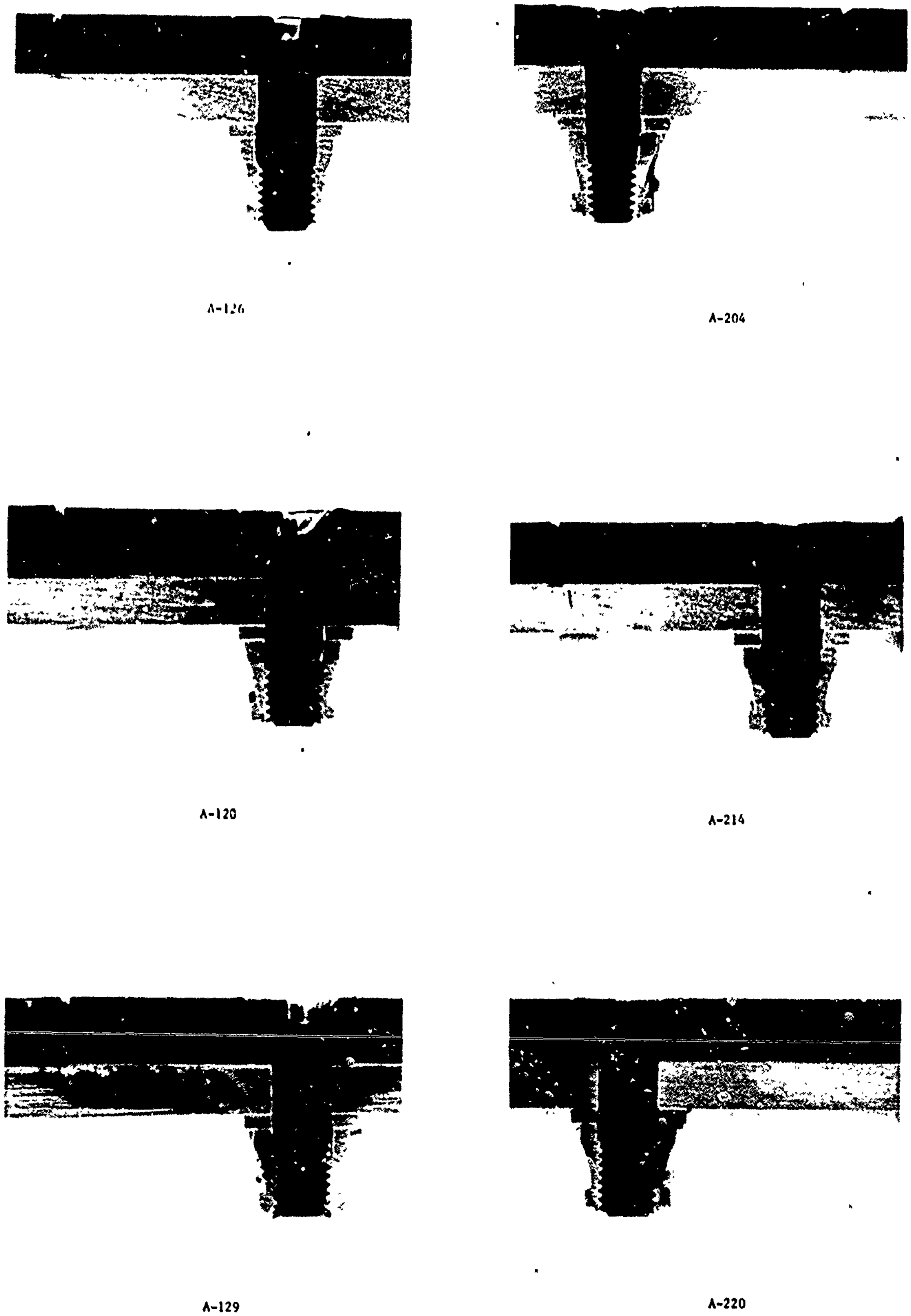

Figure 17. Test Sample Comparison, Titanium Fastener and Butt Joint Condition

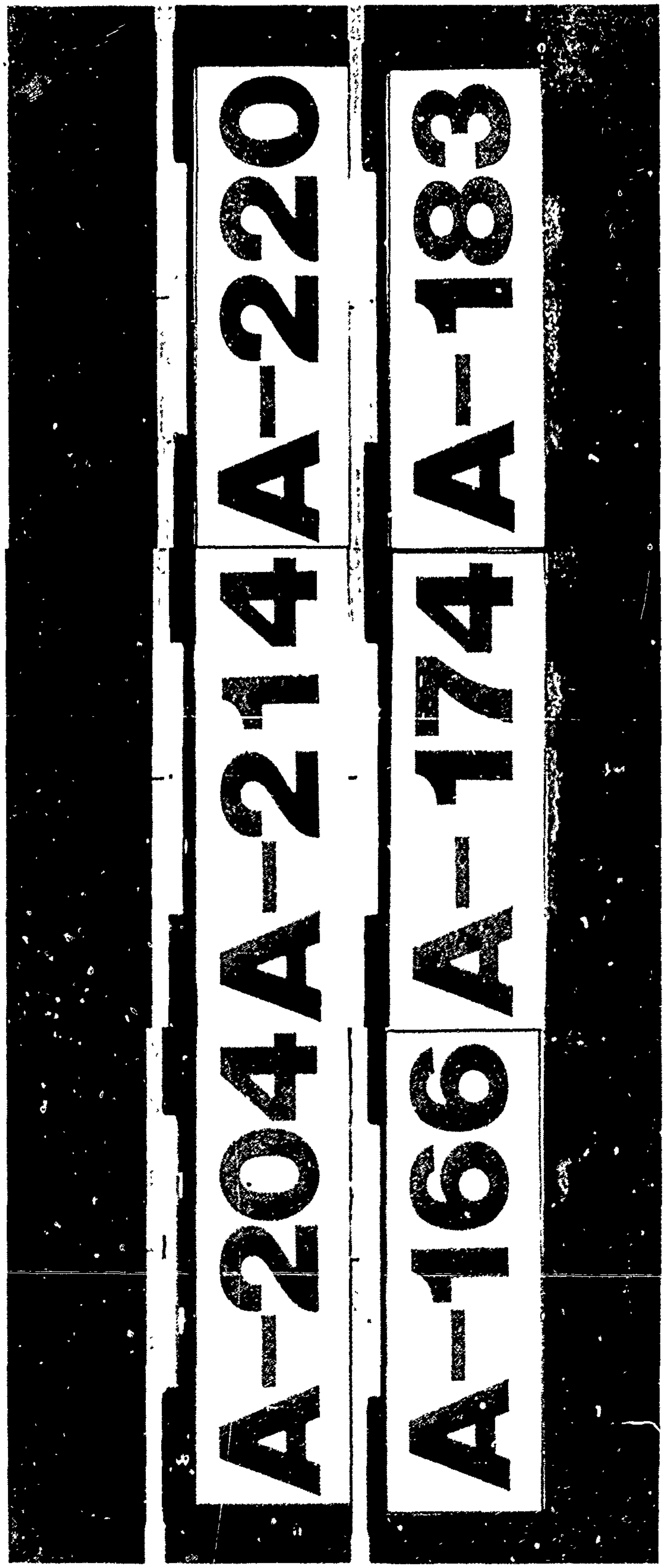

Figure 18. Protected Graphite/Epoxy and Aluminum Samples, Structure Edge Condition After Two Corrosion Cycles and One Fatigue Cycle